INSTABILITY OF FILM BOILING OF A MOVING LIQUID

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The authors examine the influence of a moving liquid on the parameters of interphase surface waves under film boiling.

One mechanism for heat and mass transfer in film boiling is the development of waves on the interphase surface, leading to the occurrence of convective mixing, an increase of the interphase interaction surface and breakdown of the vapor layer due to liquid penetrating to the heater surface. The interphase boundary waves result from interaction of infinitely small perturbations and the main flow. If the energy of the infinitely small deviations from the stationary state exceeds the dissipation energy, an instability develops.

We consider the influence of a moving liquid on the stability of the interphase surface in a coordinate system where the x axis is vertically upward along the heater surface, which provides a constant heat flux, and the y axis is normal to this surface. The planar motion of an incompressible vapor film is described by the Navier–Stokes equations [1]. We express the boundary conditions at the surface of the interphase interaction in a form which allows an end result to be obtained analytically. Using the law of conservation of momentum in going through the phase change boundary, we can write the normal and tangential stresses in the form

$$P = P_1 + j^2(1-\rho_2/\rho_1)\rho_2^{-1} - \sigma\frac{\partial^2\delta}{\partial x^2}, \tag{1}$$

$$\mu_2\frac{du}{dy} = \tau_\delta + j(W - u|_{y=\delta}). \tag{2}$$

The normal stresses (1) account for the pressure in the liquid phase, the reactive force of phase transition and the surface tension (it is assumed that $\partial\delta/\partial x \ll 1$). The tangential stresses (2) are obtained from the condition that friction is present on the liquid–vapor boundary (τ_δ) and that the momentum is transferred by the transverse mass flux $j(W - u|_{y=\delta})$. The existence of a transverse mass flux leads to the velocity profile in the liquid boundary layer being fuller than when there is no mass transfer. As a result there is an increase of the liquid velocity gradient, and a consequent increase of the tangential stress. Since it is difficult to determine τ_δ accurately, we shall assume that:

$$\tau_\delta = 0.5c\rho_1(W - u|_\delta)^2. \tag{3}$$

The kinematic boundary condition for the incompressible vapor film has the form

$$\frac{\partial\delta}{\partial t} + \frac{\partial U\delta}{\partial x} = j/\rho_2. \tag{4}$$

The similarity velocity profile is

$$u(t,x,y) = U(t,x)\left[y - \frac{1}{2(a+\delta)}y^2\right]\varphi(t,x), \tag{5}$$

where

$$\varphi = \frac{a+\delta}{\frac{1}{2}a\delta + \frac{1}{3}\delta^2};\quad a = \frac{1}{g\rho^2}\left(c\frac{\rho_1 W^2}{2} + jW\right),$$

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occurs for laminar flow of vapor and always satisfied the boundary conditions. In deriving Eq. (5) we took into account that $W \gg u|_\delta$ in most cases.

Substituting Eq. (5) into the equation of motion in Navier–Stokes form and averaging over the transverse coordinate y, we obtain

$$\frac{\partial U}{\partial t} - f_2 \frac{\partial \delta}{\partial t} + f_3 U \frac{\partial U}{\partial x} - f_4 U^2 \frac{\partial \delta}{\partial x} - \frac{\sigma}{\rho^2} \frac{\partial^3 \delta}{\partial x^3} + \nu_2 \frac{U}{\frac{1}{2} a\delta + \frac{1}{3} \delta^2} - g = 0, \tag{6}$$

$$f_2 = \frac{9a^3\delta + 18a^2\delta^2 + 11a\delta^3 + 2\delta^4}{36(a+\delta)\left(\frac{1}{2} a\delta + \frac{1}{3}\delta^2\right)^2},$$

$$f_3 = \frac{10a^2\delta^2 + 15a\delta^3 + 6\delta^4}{60\left(\frac{1}{2} a\delta + \frac{1}{3}\delta^2\right)^2},$$

$$f_4 = \frac{30a^4\delta^2 + 85a^3\delta^3 + 83a^2\delta^4 + 32a\delta^5 + 4\delta^6}{360(a+\delta)\left(\frac{1}{2} a\delta + \frac{1}{3}\delta^2\right)^3}.$$

We linearize the equation obtained (6) and the kinematic boundary conditions (4) in the neighborhood of the equilibrium state under the condition that the transverse mass flux is constant ($j = q/r$) and that the infinitely small deviations have the form of the plane waves

$$\Delta\delta = \delta' \exp i(kx - \omega t), \quad \Delta U = U' \exp i(kx - \omega t). \tag{7}$$

After transformations, taking account of Eq. (7), Eqs. (4) and (6) take the form

$$\begin{cases} \left[-\nu_2 U_0 m_{4,0} + i\left(k^3 \frac{\sigma}{\rho^2} - k f_{4,0} U_0^2 + f_{2,0}\omega U_0\right)\right]\Delta\delta + \\ + [\nu_2 m_{3,0} + i(k f_{3,0} U_0 - \omega)]\Delta U = 0, \\ (kU_0 - \omega)\Delta\delta + k\delta_0 \Delta U = 0, \end{cases} \tag{8}$$

$$m_{3,0} = \left(\frac{1}{2} a\delta_0 + \frac{1}{3}\delta_0^2\right)^{-1},$$

$$m_{4,0} = \left(\frac{1}{2} a + \frac{2}{3}\delta_0\right) m_{3,0}^2.$$

From the condition that the solution of Eq. (8) be nontrivial (equating the corresponding determinant to zero) we obtain the dispersion equation

$$\omega^2 - \omega[kU_0(f_{2,0}\delta_0 + f_{3,0} + 1) - i\nu_2 m_{3,0}] - ikU_0(\nu_2 m_{4,0}\delta_0 + m_{3,0}\nu_2) + k^2U_0^2(f_{4,0}\delta_0 + f_{3,0}) - k^4\sigma\rho_2^{-1}\delta_0 = 0. \tag{9}$$

For real values of k from Eq. (9) we can obtain a picture of the variation of the small perturbations of Eq. (7) with time. If the imaginary part of ω is negative, the perturbations are damped, and when it is positive the instability grows (convective or transport instability). The case when the imaginary part of ω is equal to 0 corresponds to the boundary of instability when oscillations will be purely sinoidal (oscillatory instability).

From analysis of Eq. (9) we can conclude that the solution

$$\frac{\omega}{k} = U_0 \frac{1+b}{\frac{1}{3} + \frac{1}{2} b} \tag{10}$$

will be real for the condition

$$k = U_0 \left\{\frac{\rho_2}{\sigma} \frac{3b^3 + 8b^2 + 7b + 2}{18\delta_0(1+b)\left(\frac{1}{2} b + \frac{1}{3}\right)^3}\right\}^{0.5}, \tag{11}$$

where

$$b = \frac{a}{\delta_0}; \quad U_0 = \frac{g}{\nu_2}\left(\frac{1}{2} a\delta_0 + \frac{1}{3}\delta_0^2\right).$$

For all perturbation with wave numbers less than those obtained from condition (11) the instability will develop as it drifts upwards with the phase velocity of Eq. (10). From these results and the relation between λ and k we can write the ratio of wavelengths to phase velocities for film boiling of a moving and a stationary liquid:

$$\frac{\tilde{\lambda}}{\lambda} = \left(1 + \frac{3}{2}b\right)\left[\frac{3b^3 + 8b^2 + 7b + 2}{54(1+b)\left(\frac{1}{3} + \frac{1}{2}b\right)^3}\right]^{0.5}, \tag{12}$$

$$\frac{\omega/k}{\widetilde{\omega/k}} = 1 + b. \tag{13}$$

It can be seen from Eqs. (12) and (13) that in film boiling an increase of the liquid velocity (the parameter b) leads to an increase of the phase velocity and a decrease of the wavelength. This change of the parameters of interphase surface waves intensifies convective mixing, and, as a result, the amount of heat transmitted is increased, compared with the case of boiling of a stationary liquid.

NOTATION

x,y, longitudinal and transverse coordinates; P, pressure; ρ, density; σ, surface tension; δ, film thickness; j, transverse mass flux; W, liquid velocity; u, longitudinal vapor velocity; μ, dynamic viscosity; ν, kinematic viscosity; $g = 9.81(\rho_1/\rho_2 - 1)$, reduced acceleration due to gravity; ω, angular frequency; k, wave number; λ, wavelength; q, heat flux density, constant over the entire heater surface; c, friction coefficient; r, heat of vaporization; 1, liquid; 2, vapor; 0, stationary value; ∿, the case W = 0; U, mean velocity; t, time.

LITERATURE CITED

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MASS-TRANSFER EFFECT IN VAPORIZTION IN VACUUM

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The results of theoretical and experimental investigation of mass transfer in the case of vaporization in vacuum from a point source onto a substrate of arbitrary form are given.

The investigation of mass-transfer processes in vaporization in vacuum is of great theoretical and applied importance, since the thermovacuum treatment of materials is widely used in energetics, mechanical engineering, electronics, and other engineering fields.

One method of investigating mass transfer is to study the condensate profiles obtained on substrates. In connection with this, it is of interest to consider a probabilistic model of vacuum vaporization in an arbitrary plane cross section of a spraying system containing a point vaporizer and a substrate of arbitrary form.

The polar coordinate system $O\rho\vartheta$ is introduced in the given cross section; the equation of the substrate then takes the form

$$\rho = \Phi(\vartheta), \tag{1}$$

where $\Phi(\vartheta)$ is a differentiable function on the segment $[\vartheta_1, \vartheta_2]$. Suppose that a source vaporizing the given interval in the time interval $[0, \tau_1]$ toward the surface in Eq. (1) is placed at point 0. It is assumed that there are no processes of revaporization or migration of adatoms of the condensate the substrate. Presuming that the trajectory of any vaporizing

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